COMBINED LOADING OF BURIED THERMOPLASTICS PRESSURE PIPES

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ABSTRACT

This paper presents the results of work that was performed at the request of TEPPFA , The European Plastics Pipes and Fittings Association, on the issue of "Combined loading" (external and internal loading) of buried thermoplastics pressure pipes.
The work is of great importance for users and designers of thermoplastics pipes. Quite often users are confused about the design of thermoplastics pipes, especially when the design is compared with traditional methods, originally developed for the design of buried linear-elastic pipe materials. Users of water mains for instance**,** demand a clear relation between the product pressure classification (PN) and the operational pressure (PFA) to be given in product standards.

Tests have been performed to check if, and to what extent, tensile stresses induced by internal pressure shall be added to the tensile bending stress induced by external loading. Tests were performed on radially deflected as well as axially bent pipes. The time to failure was recorded. It was shown that the time to failure in these combined loaded pipe samples is the same as for straight non-deflected pipe subjected to the internal hydrostatic pressure only.

Recommendations for the design of buried thermoplastic pipes both for pressure and non-pressure applications are given, based on the results found in this study**.**

INTRODUCTION

The design of buried thermoplastics pipes for pressure applications is based on the situation of free creep under the action of internal pressure. For traditional materials, the stresses induced due to internal pressure and those induced by external loading are combined as far as a simple ring evaluation is considered. When at the same time axial bending takes place, one then calculates the equivalent stress, which stress is compared with the allowable stress. The allowable stress is based on results from a tensile test.

Thermoplastic materials do not allow the combination of the bending and tensile stresses in the way suggested by most traditional design methods. The background to this is however not very well spread.
With the publication of EN805 *"Water supply-Requirements for systems and components outside buildings*" product standards are obligated to show the relation between the product related pressure classification and the system related pressure classification, involving combined loading.

For the above reasons, TEPPFA has decided to initiate a study on the issue of 'Combined Loading'. First an overview is given on the way thermoplastic pipes are designed. Attention is given to the safety factor and overall design factor approaches, which are different. Reference will be made to previous work**,** followed by results from additional tests to check / confirm previous findings. Finally an advice will be given on the design of thermoplastics pipes. Furthermore, the answer to the request of EN805 (1), to relate the product classification pressure (PN) to the allowable operating pressure (PFA), will be given.
In EN805 (ref. 1), PFA – the allowable operating pressure- is defined as the maximum hydrostatic pressure a component is capable of withstanding continuously in service.

TRADITIONAL DESIGN OF BURIED PIPES

Pipes buried in soils are loaded by soil and traffic. Furthermore, prescribed displacements due to settlement and subsidence of the soil occur.
The traditional design of buried pipes is based on experience and knowledge gained with linear elastic materials. The verification against limit-state of pipes is done using the traditional material models. In most regions in Europe for thermoplastics pipes, however, the PN rating on the products is used for determining the allowable operating pressure.

Linear elastic materials have a unique limit state stress or strain, whereas thermoplastics materials with their visco-elastic behaviour exhibit a range of failure strains / stresses. For the failure model it is of great importance to know if the material is loaded by constant load or if the load is not able to follow the deformation of the material. In the latter case, stress relaxation will occur. In traditional failure mechanics this means that the stress at a crack tip vanishes and crack growth is arrested. The ability to redistribute (peak) stresses in combination with a relative huge yield potential is a great feature of thermoplastics. Involving all these aspects in the definition of an analytical failure model would become a difficult job. For that reason, tests have been developed to verify the strainability of these materials for its application.

SAFETY FACTOR VERSUS OVERALL DESIGN COEFFICIENT

For traditional elastic materials safety factors related to maximum allowed stress or load can be defined. The value, however, is valid for the initial conditions. For traditional elastic materials it is considered that this initial condition does not change in the course of time and hence claimed to be independent of lifetime. For thermoplastics, safety factors can be defined, related to the stress and also to time.
For traditional materials usually the prediction of deterioration, like corrosion, of the material is not known and hence safety factors relating to these aspects are not given.

Safety factors as traditionally anticipated have no meaning for thermoplastics materials. When the stress increases temporarily over the MRS value, then immediate failure will not be the result, which is contrary to traditional materials. Only when the stress is exceeding the MRS value for a long period of time, failure might be the result, but only then when the condition of sustained creep is fulfilled.

It has been explained that for thermoplastic materials, the traditional safety factor approach is not relevant. Therefore, the so-called Overall Design Coefficient (C) has been introduced. This factor covers the effects of handling, scoring, etc.
Table 1 shows the factors for C for Gas and Water.

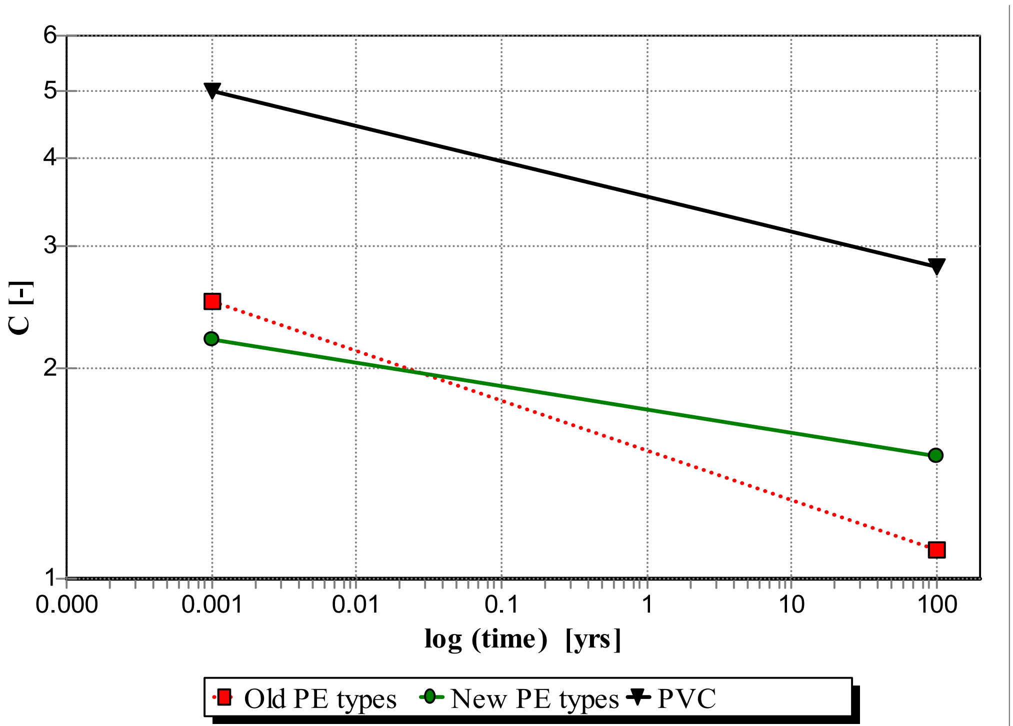
Table 1 : C-factors commonly used for design on pressure

Material	Water	Gas
PE	1.25	>2.0
PVC	2.0 (d> 90 mm)	)1
	2.5 (d≤ 90 mm)	
Oriented PVC	1.6	

)1 due to low distribution pressure in PVC, stiffness is the governing design parameter.

The factor C is related to a 50 years lifetime for a condition of free creep at 20 ˚C.
The effective overall design coefficient can be plotted against the free creep period, which is the period at which the pipe is experiencing a constant internal pressure at a constant temperature of 20 deg C, without being hindered by outside soil pressures. The principle is shown in Figure 1.
In reality pipes in soil do not experience a free creep condition, except in very soft soils.

Figure 1: Effective overall design coefficient C'(for water applications)



For the purpose of designing pipes in practice, the factor C is related to a free creep period of 50 years at 20 deg C.
The graph shows also that the factor at 100 years is almost the same as the value for 50 years. Next to the fact that most commercially available materials have strength values far above the MRS value. Therefore it can be stated that the C factor for 100 years practically equals the values given in table1.

EXPERIMENTAL

Two types of combined loading tests have been carried out. The first tests, internal pressure tests on deflected pipes, simulate the situation where a pipe is deformed by the soil, traffic and installation. The pipe deflects after which internal pressure is applied. The second test, internal pressure tests on axially bent pipes, simulates pipes that are bent in the field and by that subjected to ring deflection and at the same time exposed to internal hydrostatic pressure.

Results on deflected pipes.

Several different materials have been tested. Standard PE80 and PE100 materials, but also extremely poor PE80 materials have been tested. These latter tests have been performed to check if brittle type of failure will be affected by combined loading effects. In tests on standard materials possible effects on ductile failure type will be observed.
The main results have been summarized in Table 2. The experiments have been performed at various internal pressures resulting in tangential wall stresses indicated in Table 2. The results on these tests on deflected and non-deflected pipe samples are expressed in a factor t x%/ t 0%, in which t_x% is the failure time for the pipe with x % deflection and t_0% is the failure time for 0% deflection.

Table 2 : Condensed results of combined loading tests on deflected pipes.

Material	Stress [MPa]	T[˚C]	(δ/d) [%]	t_x% / t_o% [-]	Remark
PE100	12.5	20	0	1.00	ductile failures
			8	1.83	
PE80	5.9	80	0	1.00	ductile failures
			5	616.00	
			10	647.00	
PE80 brittle grade 1	4.5	80	0	1.00	brittle failures
			5	1.05	
			10	1.07	
PE80 brittle grade 2	4.0	80	0	1.00	brittle failures
			12.5	1.14	
PVC Bi-axially oriented pipes	26	60	0	1.00	ductile failure
			5	4.14	
			10	8.73	

This table shows that deflected pipes have significantly lower failure times than non-deflected pipes when internally pressurized and the failure type is ductile.
For brittle failure type defected pipes also show slightly longer failure times than non-deflected pipes. From these results for thermoplastics (PE and PVC), the following can be concluded:

1. The combination of stresses induced by internal pressure respectively external loading does not result in shorter failure times like for traditional materials.
2. For materials failing in a ductile manner, deflection increases the time to failure.
3. For materials failing in a brittle way, deflection has a slightly positive effect on time to failure.
4. The failure processes are not accelerated by deflection of the pipes.

Results on bent pipes

This type of test was first performed by Wintergerst (ref. 2) in order to verify if it is allowed to make a cold bend in the field, a feature of thermoplastics pipes.
He already carried out these tests on PVC and PE pipes in the seventies. Some additional tests have been performed here to verify if the results are still valid for the modern PE and PVC pipes.

When internally pressurized pipes are bent, axial stresses and strains develop. Here the load is also a prescribed displacement. That means that the stresses again relax in the course of time. Wintergerst has performed several tests in which internal pressure was combined with bending stresses and strains. (ref. 2)
A pipe is bent over a pre-shaped curvature. That means that the pipe is bent to a curvature (R). By bending the pipe it deflects to a value of (δ/d). The strain at the outer fibre is the distance from the neutral axis to the outer fibre divided by the curvature R.

The following formulas apply:

Pipe ring deflection as a result of axial bending of the pipe can be expressed by:

$(\delta/d) = 1/16 * (d/s)^2 * (D/R)^2 * (1-v^2)$ ……………………… ..(1)

This ring deflection results in a hoop bending strain described by:

$\varepsilon_o = 3 * (\delta/d) * (s/d)$ ……………………………………..(2)

The axial bending over the radius results in an axial strain of

$\varepsilon_{ax} = (D-((\delta/d)*d)/2)) / (2*R)$ ……………………….. (3)

In which:

(δ/d)	Pipe ring deflection due to bending	[%]
d	Average pipe diameter	[mm]
R	Bending radius	[mm]
D	Outside pipe diameter	[mm]
v	contraction coefficient	[-]
ε_{ax}	Axial bending strain	[-]
ε_o	Hoop bending strain	[-]

Wintergerst tested several PVC and PE pipes of 63 mm and bent the pipes to 17*d and 25*d for PVC pipes.;for PE pipes he used 10*d and 25*d. The results of the internal pressure tests on bent pipes were then compared with those from the straight pipes. His conclusion is:
"For the combination of internal pressure and bending radii of 17 and 25 times the pipe diameter, no significant effect on time to failure is found for PVC." "For the combination of internal hydrostatic pressure and bending radii of 10*d and 25*d, no effect is found for PE pipes."
An example is taken from his test results and analysed with respect to combined loading.

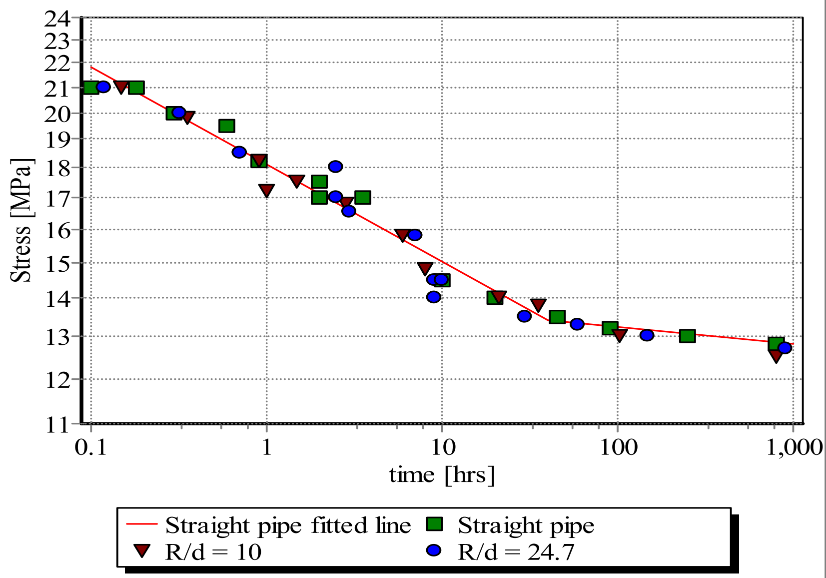
Example analysis of Wintergerst result:
The graph produced by Wintergerst is shown in Figure 2.
The PE material used is a GM5010
Pipe sample : 63 x 5.7 mm
Mean diameter Dm = 63-5.7 = 57.3 mm
s/Dm = 5.7/57.3 = 0.1
The bending radius used is 630 mm.
The ovality due to bending (from equation 1) results in a pipe deflection of 5%.
The circumferential strain (from equation 2) becomes 1.5%
The axial strain due to bending (from equation 3) becomes 4.8%
The circumferential stress becomes with Hooks law:

$$\sigma_0 = E(t) * \varepsilon_o \qquad (4)$$

The stresses become now for: time = 3 min , E(3)= 900 MPa σ (3) = 13.5 MPa
time = 1 h , E(3)= 500 MPa σ (3) = 7.5 MPa
time = 200 h , E(3)= 200 MPa σ (3) = 3.0 MPa

According to figure 2, short-term failure comes up at a constant tensile stress of 21 MPa. Simultaneously the bending stress is 13.5 MPa, due to bending of the pipe over a radius of 630 mm. After 200 hrs with constant tensile stress of 13 MPa failure occurs. During this 200 hrs the bending stress has relaxed from 13.5 MPa to 3 MPa, etc. The total stress after 200 hrs is thus 13+3 = 16 MPa. If the bending stress of 3 MPa has had any influence on the strength of the pipe, the failure should have occurred already after 4 hrs, according to figure 2.
Thus the combination of loading by internal hydrostatic pressure and ring ovality due to pipe bending gives the same time to failure as loading of a straight pipe with internal pressure only.

Figure 2: Results obtained by Wintergerst on PE.

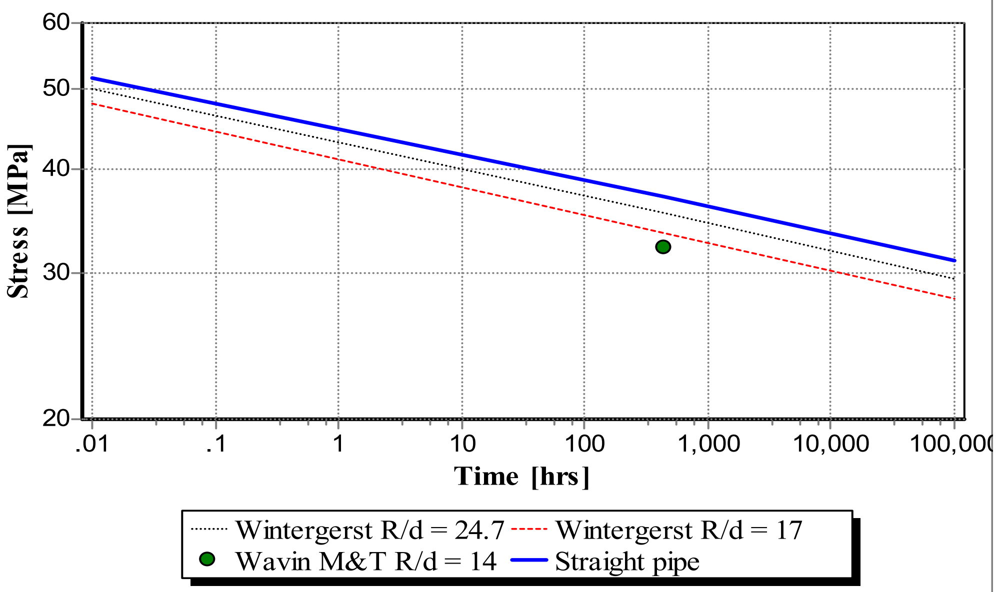


The results published by Wintergerst, were obtained with PE types used in the early seventies. PE has been improved since then, and a higher relaxation rate, resulting in a better ability to redistribute stresses. Therefore, additional tests have been performed, which confirmed the findings of Wintergerst also to be valid for the current PE types.

Wintergerst showed that for PVC extrapolation of the results leads to an MRS value still exceeding 25 MPa. This work was carried out in 1973. During the last 30 years, great improvements both in the field of raw material development and processing have taken place. Therefore, additional tests were performed on PVC pipes with an even smaller bending radius than used by Wintergerst. The results of these tests are plotted in figure 3 together with the results of Wintergerst.

The results of the tests performed by Wintergerst are shown for two different R/d ratio's.
It is shown that ratios down to 24 do not affect the design stress significantly. An R/d of 17 and 14 shows to have some effect on design stress. Pipe bending radii in the field are limited to R/d = 100, which is far above the values used here.

Figure 3: Summary of Wintergerst test completed with characteristic result of M&T tests.



DISCUSSION

Combined loading tests have been performed to determine to which extent the effect of external loading affects the time to failure. The tests performed can be considered as rigorous and present worse case conditions. The test chosen is a parallel plate loading, where the pipe is deformed up to high deflection levels by which bending strains and stresses are created. In real life, pipes will reround to some extent when pressurised. In the parallel plate loading test, the re-rounding cannot take place. In practice however the pipe is embedded in soil. Next to the fact that the pipe deflects due to the non-axisymmetric portion of the soil pressure, it also experiences radial soil pressure. The latter balances the stresses due to internal hydrostatic pressure to some extent. In the test this is not the case. Some of the deflection levels used are significantly higher than in reality. Pipes having stiffness of 8 kPa and higher will not deflect to levels of 10%. In the tests however, these levels have been used as well.

It has been shown that stresses caused by internal hydrostatic pressure cannot be added to those induced by external load for the determination of the time to failure. A thermoplastic material does not follow the same rules as those of the traditional elastic materials. The features responsible for this, are the huge strainability of the thermoplastic materials and the stress relaxation phenomenon.

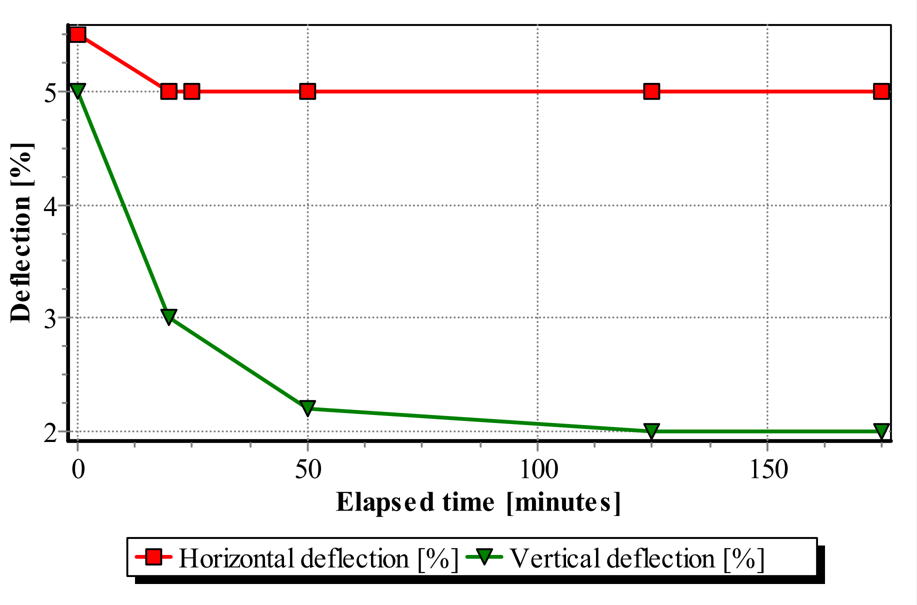
The above means that for design one cannot use the traditional approaches as valid for elastic materials.
For thermoplastics one need to carry out a two step approach. The pipe shall first be designed solely as a gravity pipe and secondly as a pressure pipe only. It shall be checked which of the two is the decisive one and dimensioning should be based on that.
The TEPPFA graph can be used as a simple way to design a pipe under gravity condition. However, in Europe several methods exist that claim to predict the pipe performance as well. Even if one of the European structural design methods is used, it is still good practise to check the result against the earlier mentioned TEPPFA graph.
For the buckling design reference is made to Janson (ref**.** 3)

In the thermoplastics industry, the use of a so-called overall design coefficient has become a common approach. These factors cover the traditional safety factor against overloading and the effects of handling and storage. The whole design of pressure pipes for the pressure component is based on test results for free creeping pipe samples under internal pressure. Considering the fact that pipes which are deformed show the same or a better performance under internal pressure than those without deformation, and the fact that pipes which stay deformed in the ground cannot fully expand, it can be concluded that the whole design is very conservative. Therefore in reality, the actual level of the factor of safety is much higher than assumed for the design of the pipe.

By Alferink and Wolters (ref. 4), exercises with the cumulative damage theory have been performed, analysing the effects of point loading on different types of PE. There it was shown that the speed of relaxation is of significant importance for the lifetime of the pipe. A high relaxation speed favours a long lifetime. Limiting or preventing full creep is in that respect as important.

In several design methods, re-rounding is an issue for pressure pipes. The above has already shown that from a stress design point of view, re-rounding is not an important issue. A few tests have been performed in the eighties to study re-rounding. In a field study vertical and horizontal pipe deflections were measured before, during and after pressurisation. This work was done on PE100 SDR 26 pipes. From the work performed in Denmark (ref.5) the following graph is shown (fig. 4).

Figure 4: Re-rounding test on PE100 SDR26 pipes at the Wavin test site "Hammel" Denmark.



The internal hydrostatic pressure was 6 bar. The graph shows that the vertical deflection is much more affected by the pressure than the horizontal diameter. The vertical deflection decreases from 5 to 2 % deflection and the horizontal deflection only changes with 0.5 %. What happens is that the diameter of the pipe extends slightly. That overall diameter extension is used to make up the vertical diameter increase. The horizontal diameter does hardly change, which is also logical. When the horizontal diameter has to decrease, it has to act in the opposite direction as the internal pressure. If full re-rounding does not take place, such being the case in firm soil, full creep is excluded.

CONCLUSIONS

External loading caused by installation, soil and traffic results in pipe deflection and bending stresses. The bending stresses are relaxing in the course of time. The additional stresses caused by external loading do not result in reduced failure times when the pipes are internally pressurized. Pipes failing in a ductile manner even profit a lot from combined loading, the time to failure increases. Pipes failing in a brittle manner are not affected by combined loading.

It is shown that the visco-elastic behaviour of materials such as PE and PVC is a profitable feature providing a long life for thermoplastics pressure pipes.

RECOMMENDED DESIGN PROCEDURE

Thermoplastics pressure pipes buried in the ground, such as those made out of PE and PVC, shall be designed in the following way:

The pipe shall be considered without bending stress caused by pipe ring deflection, as this stress is relaxing in the course of time (ref.3).

Therefore the design shall be based on internal pressure only, and in addition, whatever application, on buckling resistance, taking external soil load and surge pressure into consideration.

In product standards of thermoplastics the relation between PFA and PN is given by:

$$PFA = ft*fa*PN \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5)$$

in which:

PFA	the allowable operating pressure a component can withstand continuously in service.
fa	the application factor, considering the effects a specific application might have on the PFA pressure.
ft	the temperature rating factor as given in the product standards.
PN	is the nominal allowable pressure allowed in the buried pipe.

The values of ft (temperature rating factor) are very much material dependant, reason why they are mentioned in the product standard.

The value for fa can be set to 1 when the following conditions are fulfilled:

- Deflections are limited to 12.5 % at a maximum.
- Bending radii are R/d > 50 * d for PVC as well as for PE in case of cold bend pipes
- Water, gas or sewage is transported. In case of chemicals advice shall be sought at the manufacturer, because certain chemicals might affect the strength of the material.

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Further information on this subject can be obtained at TEPPFA's office in Brussels, attn of Mr. Tiem Meijering.

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